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DEPARTMENT OF THE ARMY
Fort Detrick
Frederick, Maryland

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BOOK I

Fundamentals and Limitations of Cyclone Dusting, by P. Rosin, E. Rammler and W. Intelmann, Dresden

Theroetic fundamentals. Degree of dust deposit and grain dimension curve. Ideal cyclone dusting procedure. Dependence of the calculated degree of deposit on entering velocity, viscosity of the carrying gas, dust fineness and volumetric weight, cyclone construction measurement and dust rotation number in the cyclone; disturbance effect. Grain composition of the separated and escaped dust. Cyclone connection in series or in parallel. Degree of quality.

The cyclone, the most important representative of the centrifugal force separators, is widely distributed throughout the various branches of industry. Constructive simplicity, inexpensive, limited use of space, limited attendance and upkeep requirements, high operative safety represent it profitably. The cyclone therefore also plays a great part in the field of coal dust, in the stack-- and interior dusting of brown-coal-brickette factories, in air separator- and dust removing installations of bituminous coal projects, in drying and painting installations; it reached a new field of application in smoke gas dust removal. Surprisingly, the knowledge of this method of elimination hardly corresponds to its great field of application, despite the fact that a few formulations of a cyclone theory have already been published. Therefore, until recently, it was impossible to determine whether the often unsatisfactory cyclone degree of deposit is controlled by natural laws or whether it is capable of improvement, for example by more careful analysis of the laws of aerodynamics. The development of thermodynamic mechanisms was greatly increased

by the fact that the thermodynamic industry succeeded in establishing ideal methods, which outlined the naturally imposed boundaries of the technical process, with the help of which it became possible to establish the relationship between fact and possible fact, by using data on thermic, thermodynamic rates of output. Similar abstracts are still completely lacking in the field of dust removal methods. A first attempt is made here to determine the limits of cyclone dust removing rates as controlled by natural laws, and to recognize those of limited size according to the type and importance of their influence. Nearly two years ago, the state coal commission accorded us such a project of cyclone theory research, which was to clarify the relation between cyclone power consumption and deposit rate and constructive and industrial conditions.[1]

Presuppositions

The formulations of a cyclone theory up-to-date are mainly confined to calculating the separation speed of a single cyclone wall particle.[2] We must therefore find the bridge leading to the calculation of the rate of dust

Note 1) P. Rosin expanded on the data from theoretic research in the lecture "Boundaries of Cyclone Dust Removal" during the meeting on light ashes questions organized by the coal dust section of the state coal commission on 12 February 1931 in Berlin. These tests and their influence on the dust chamber were further treated by E. Rammler on 15 May 1931 in Gottingen, in his work "Aerodynamic Problems in the Dust Removal Technique". The research on the centrifugal force separator theory with the research data on cyclone power consumption and deposit rate will appear in detail in book form. We thank Dr. Eng. Kayser, Dresden for suggestions.

Note 2) Forderreuther, Wirkungsweise von Staubsichtern und Staubabscheidern, Arch. Warmewirtsch. Bd. 10 (1928) S.323; - M. Seillan, Uber Fliehkraftabscheider, Chaleur et Ind. Bd. 10 (1929) S.233; - Fr. Prockat, Glasers Ann. Bd. 106 (1929) S.73 u.f., Bd. 107 (1930) S.38 u.f.

removal of the ideal process, in the total curve of the material on hand and also in its analytic equation. This ideal process is characterized by the following hypotheses: The Stokes Law is valid for the previous grain volume. The particles are considered spheres. The dust in the entering cross section is equally distributed throughout the entire cross section both in density and fineness. The particles do not influence one another in their movements. Re-whirling of the particles already deposited on the cyclone wall does not take place. During the entire possible separation path the gas ray is kept at the width and height established through the right angles entry cross section. Rotation free flow acts within the separation path. A simple assumption will be established for course of the velocity profile over the width of the entrance cross section.[3] This velocity profile is always the same for the height of the entrance cross section. It is maintained for the entire possible separation path. The carrying forces may be ignored. Let all fluctuations of these ideal results due to practical situations be called disturbance functions.

Symbols

The designation will be as follows:

x The grain size = grain diameter in m

v The in blowing velocity in m/s

r The actual greater distance of a particle from the cyclone axis in m

D The cyclone cross measurement in m

s = D - r The actual particle distance from the cyclone wall in m

Note 3) The velocity profile of the ideal process should be defined as a two way parabolic surface established over the basic cross section, so as to remain in formal agreement with the laws of aerodynamics. For, despite the fact that the calculations became very complicated, it was assumed that the velocity was constant on the entire cross section and equal to the mean in blowing velocity, without greatly changing the data.

i The entrance cross section width in m

h The entrance cross section height in m

γ Dust volume weight in Kg/m^3

δ Dust contents, dust quantity in 1 m^3 of gas, in Kg/m^3

n The gas viscosity in Kgs/m^2

U Circulation of the dust particle in the cyclone

$R = f(x)$ The total dust sediment given up by the cyclone on a covering strainer in %

$R' = \varphi(x)$ The same for the dust deposited in the cyclone in %

$R'' = \psi(x)$ The same for dust which escaped from the cyclone in %

Calculation of the ratio of dust elimination

From the formulation, that under similar weight circumstances the flow resistance forces in the carrying gas and the particle escape force are equal to one another, and assuming that, the velocity over the entire cross section of the circulating blast may be set constant and equal to the in-blowing velocity, for the separation velocity, with which a segment of the gas stream will be lost in a vertical direction to the latter, giving the relation

$$v_a = \frac{dr}{dt} = \frac{1}{18} x^2 \frac{\gamma}{ng} \frac{v^2}{r} \qquad (1).$$

The cyclone theories formulated up-to-date have not succeeded in calculating separation velocity and its graphic representation. We were able to establish the relationship between separation velocity and rate of deposit by using the granulation characteristic (graph) of the dust to the deposited, as it takes place through screens and wind filters. We have studied the characteristics of this graph for years and have, in most cases, been able to draw its analytic relationship.

By separating the variables and by integration, and with care to replace $t = 0$ with $r = D/2 - s$, from Eq. (1), we have:

$$r^2 = \frac{x^2}{9} \frac{y}{ng} v^2 t + \left(\frac{D}{2} - s\right)^2.$$

By replacing $t = \frac{\pi D}{v} u$,

and $\qquad r = D/2$

solving for x, we obtain the grain dimension of the smallest particle which still travels towards the wall from distance s, as

$$x_{min} = 3\sqrt{\frac{ng}{yv}}\sqrt{s\left(1 - \frac{s}{D}\right)\frac{1}{u}} \qquad (2).$$

These considerations apply to single particles of a given grain dimension. Actually the material to be deposited usually consists of an uninterrupted bond, in which all grain sizes are represented arranged according to a law of distribution from a lowest to a highest value. This relationship is illustrated by the curve, which gives the relationship between the total deposit R and the filter mesh width (grain dimension):

$$R = f(x)$$

So as to pass from the laws controlling the single particle to those of the total dust, let us consider a differential gas volume of size h ds dl at distance s from the cyclone wall at the moment of penetration into the cyclone, Fig. 1 (dl signifies the vertical depth to the image level). The contained dust volume is

$$dq = h \; ds \; dl \; \delta.$$

All grains greater than the value x_{min} calculated in Eq. (2) are eliminated, i.e.,

$$dq = h \; ds \; dl \; \delta \frac{R_{x_{min}}}{100}$$

$$= h \; ds \; dl \; \delta \frac{f(x_{min})}{100}.$$

The rate of deposit for the volume element considered, or for the infinitely thin layer h ds at distance s from the cyclone wall is calculated as

$$x_s = 100 \frac{dq_a}{dq} = f(x_{min}) \text{ in } \% \qquad (3).$$

The total rate of deposit is arrived at from this partial rate of deposit through integration of the total width of the entrance cross section:

$$a = \frac{1}{i} \int_0^i a_s \; ds = \frac{1}{i} \int_0^i f(x_{min}) \; ds \qquad (4).$$

Fig. 1

Cross section of the cyclone entrance

h Height of the entrance cross section

i Width of the entrance cross section

s Particle distance from the cyclone wall

Fig. 2

Graphic representation of the rate of particle deposit.

$D = 3m$; $v = 20m/s$; $\gamma = 1200\ kg/m^3$;

$n = 1{,}83.10^6\ kg\ s/m^2$; $u = 1$

Example: Wanted rate of particle deposit for $s = 0{,}1$.

From $s = 0{,}1$ in diagram I draw a horizontal (line a) to the curve, a perpendicular line from here (line b) to the grain size graph in diagram II and then horizontally towards diagram III (line c) to the point of crossing with the perpendicular (line d) from $s = 0{,}1$. The ordinates of this point of crossing give the desired rate of particle deposit.

The presuposition for evaluation of these relations is that the curve actually exists graphically, whereby the grain range under the Nr. 100 filter mesh width (60 u) is to be divided into at least three, or better four fractions by air filters, sedimentation or washing. The curve of the smallest, still to be deposited grain size x_{min} qualified by value s is entered in square I of Fig. 2, from which one may calculate x_{min} according to Eq. (2) for the relations on hand; the entire curve of the dust to be deposited is entered in square II, using the ordinate axis of the x_{min}-curve as a basis. The size of s is again entered on a free axis in square III. The two s-axes are now divided into respectively appropriate sections, ordinates are constructed, these bisect

the x_{min}-curve in square I, line a, from here follows the s axis to the curve, line b, and from here on line c to the bisection of the corresponding ordinate d in square III. The rate of particle deposit curve a_s is obtained in square III through repetition of this construction. The total rate of dust removal a is finally obtained by surface measuring the area under this curve divided by the entrance cross section i. The rate of deposit for the given example of a thin layer on the wall amounts to 100%, drops to 90,6% for such a layer 2 cm from the wall; at 20 cm distance it drops to 73,3 and at 50 cm distance to 6,2%, the total deposit amounts to 73,7%.

The curves of both ground and natural dusts, such as light ashes, may be expressed by the exponent-function:

$$R = 100\, e^{-bx^n} \text{ in } \%$$

where b and n are constants. In this case, the relation for the rate of dust removal is:

$$a = \frac{1}{i} \int_0^i e^{-bx_{min}^n}\, ds$$

$$a = \frac{1}{i} \int_0^i e^{-b\left[\frac{9}{2}\frac{ng}{\gamma v}\, s\left(1 - \frac{s}{D}\right)\frac{1}{U}\right]^{n/2}} ds \qquad (5).$$

Here too, the integration follows graphically.

Dimensions influencing the rate of dust removal

The dimensions obtained in Eq. (5) influencing the rate of dust removal may be included in such as that of the carrier gas (in blowing velocity v, viscosity n),

that of the material on hand (Fineness, given in b and n, specific weight γ) and that of construction (cyclone D cross measurement, entrance cross section width i, circulation value U). The influential dimensions not included in Eq. (5), such as dust contents , are to be united in the concept of factors of disturbance. From the construction of Eq. (5) it is evident, that the dimensions conditioning the rate of dust removal build up a complex; we will only be able to list a small part of our calculation and research data.

In-blowing velocity

The rate of dust removal according to Fig. 3 for 20% coal dust deposit on filter Nr. 70 is 49% for 5 m/s in-blowing velocity; 66.5% for 15 m/s; 73.5% for 25 m/s; 78.5% for 40 m/s. The rapidly mounting curve flattens out in proportion to the in-blowing velocity. Therefore, little can be won above 25 m/s even in theory, especially when one considers the mounting pressure requirement (pressure loss). But the rise of in-blowing velocity increases the danger of a stirring up of the just deposited dust more than proportionally; so that actually the curve levels off much more rapidly than indicated in the theory, see Fig. 4, which was determined on a 400 mm cross section cyclone model. It might even occur that the curve sinks as a result of this disturbance. The values of suspended ash (in air) of identical fineness are from 6 to 8% higher because of the greater specific weight caused by the contents of combustible material.

Viscosity

The influence of smoke gas viscosity is limited within the temperature interval of 150 to 350° considered for suspended ash deposit. The rate of dust removal in this case drops from 77.5 to 75%, with 20 m/s in-blowing

velocity, suspended ash of $y = 2200$ kg/m^3 and other conditions equal to those given above. Each boiler changes with the boiler load as well as with in-blowing velocity and temperature of the heat gases during suspended ash deposits through a single cyclone. The rate of dust removal should rise when affected by the first and fall with the second, when the load is increased and all other conditions remain equal. The influx of the growing entering velocity is greater than that of the rising temperature, chiefly because the entering velocity rises much more than proportionately owing to two reasons, greater coal consumption and higher exhaust-gas temperature. Furthermore the suspended ash particles will become larger with a boiler load increase; the cyclone rate of dust removal therefore rises with growing boiler load.

Fineness

The fineness influx is easily seen in Fig. 3, in which the deposit on filter Nr. 70 was chosen as parameter; the relationship appears more clearly in Fig. 5 for example, considering a circuit and 15 m/s in-blowing velocity a 66.5% yield is obtainable with 20% deposit on filter Nr. 70, 76.5% with 45%/Nr. 70; the corresponding boundry values for 25 m/s are 73.5 and 80%; finally for 40 m/s they are 78.5 and 83.5% (all for brown coal dust). The fineness influx therefore drops with growing in-blowing velocity.

Fig. 3

Total rate of dust removal for a cyclone of 3 m in diam. depending on the in-blowing velocity and the dust fineness for an entrance cross section breadth of 0.5 m and a (20°) carrying gas circuit within the cyclone.

Fig. 4

Total rate of dust removal for a 400 mm cyclone depending on in-blowing velocity.

Fig. 5

Rate of deposit depending on fineness in-blowing velocity from 1 to 4 carrying gas circuits within the cyclone.

D = 3 m; i = 0.5 m; y = 1200 kg/m^3; t = 20°

Fig. 6

Rate of deposit depending on specific weight (weight by volume) D = 3 m; i = 0.5 m; U = 1; v = 20 m/s; t = 20°

Fig. 7

Rate of deposit for a 3 m in diam. cyclone depending on the entrance cross section width and the in-blowing velocity.

Fig. 8 and 9

Influence of the cyclone cross measurement.

$v = 20$ m/s; $U = 1$; $t = 20^{\circ}$; 27% deposit on filter Nr. 70

Fig. 8

Entrance cross section width is constant.

Fig. 9

Relation of the entrance cross section i to the constant cyclone cross measurement.

The influx of greater fineness can again be theoretically levelled off by increasing the in-blowing velocity. But it soon finds its practical limit, as the danger of disturbing the deposited dust rises from two causes: growing in-blowing velocity and additional fineness.

Volume weight

If the rate of brown coal dust deposit attains 73.5%, suspended ash under similar conditions as shown in Fig. 6 especially of equal fineness, reaches 80, cement 82.5, barite 85.5% and iron filings 88.5%; the curve therefore keeps getting flatter in proportion to growing volume weight y. The cyclone will deposit this circuit of low combustible contents suspended particles more easily than one of high suspended coke contents. Selective deposition acts

against this fact, as the suspended coke particles are usually found in coarser fractions. Furthermore suspended cinders often form light, hollow spheres, difficult to deposit.

Width of the entrance cross section.

The smaller the entrance cross section of a given cyclone, the smaller will be the escape paths to be measured, and the higher will be the rate of dust removal. For example, the theoretical rate of dust deposit in Fig. 7, given in 3 m cyclone cross measurement and 25 m/s in-blowing velocity, is 88% when the entrance cross section is 0.1 m wide, and drops to 69.5% for a 1 m entrance cross section width. Unfortunately the possible use of a narrow entrance is limited in practice. For the cyclone load possibility drops with decreasing cross section width if the height of the cross section is not proportionately enlarged. However this limitation of the flow soon reaches constructive limits.

Cyclone diameter

If the absolute width of the entrance cross section were to be kept constant, the rate of dust deposit would be subject to very slight change during increasing cyclone diameter, Fig. 8. Such an enlargement law is impossible, as it would rule out a possible rise in cyclone load increase; this however is the reason for diameter enlargement.

If the relation between entrance cross section width and the diameter is kept constant - a magnification rule followed by a great number of firms - the rate of dust removal drops sharply with growing cyclone diameter, Fig. 9. However, as stated above, this influx depends mainly on the growth of the absolute width of the entranse cross section.

Unfortunately the fact that small model cyclones yield higher rates of deposit than large enterprises is often disregarded. The characteristic cyclone procedures are very complicated, and this is not the place to discuss them. However it should be pointed out that a great number of differences between model and actual test stem from the narrow entrance cross section, usual in such experimental cyclones. It is possible to review this section with the help of Fig. 8, and to compute such research values approximately for larger cyclones.

Circuit value

The above calculations were mostly conducted according to the simple assumptions, that the actual deposition terminates with a single gas blast circuit through the cyclone. The following figures drawn from Fig. 5, show how much the deposition may be improved by repeated circuits without stirring: for example the dust removal rate of 25%/Nr. 70 brown coal dust at 20 m/s in-blowing velocity is 72.5% for one circuit, it rises to 79.5% for two passages, to 83.5% for 3 and finally to 85.5% for four passages. The curve keeps getting flatter as the number of circuits increases, so that weight improvements are not possible after 3 to 4 circuits. Fig. 5 further indicates that the influence of both in-blowing velocity and of fineness decreases in proportion to increased numbers of circuits.

Disturbance influences

Disturbance influences, beyond calculation, overlap the developed theoretical calculating rules; with practically a single exception of dust contents they try to change the theoretical rate of dust removal, so that one has to multiply it by a quality rate which completely reflects the thermodynamic work

rate of the steam engine. Stirring is a part of disturbance influences - already present in the penetrating gas, increased by wall friction, the push of the active gas blast upon the newly entering gas, the friction between various blast velocities, distortion of the original velocity profile and of the blast measurements, tearing of pre-deposited particles from the cyclone wall by stirring, etc. In fact we conducted our model tests under aerodynamic conditions in an attempt to improve cyclone quality rate and energy consumption. The results of these tests cannot be given within the frame of this paper. Let it only be mentioned in connection with these tests, that they also follow a number of construction conditions which cannot be calculated, such as entrance cross section height, height of the cylindrical section, cross section and penetration depth of the exhaust tube, further installations in their influence on dust removal rate and pressure need.

Deposited and escaped dust grain conglomeration.

All grain sizes, which are above the minute grain dimension x_i, which still is being deposited within the interior edge of the entrance cross section, Fig. 1, are completely deposited under the above conditions. This grain dimension may be described as the "ideal pore width" to quote an expression by Meldau. It is achieved by placing s = 1 in equation (2). Grain sizes inferior to x_i are only partly deposited and therefore are partly in the deposited mass, partly in the pure gas. One therefore simply obtains the filter deposit of a deposited mass on mesh larger than x_i, by dividing the respective deposit of the test material by the cyclone rate of dust removal:

$$R' = \frac{R}{a} 100 \qquad (6).$$

One may obtain the curve for the deposited dust by filtering up to a possible degree, as the ideal mesh opening is usually below 40 u, and the finest filter Nr. 100 has a mesh opening of 60 u. The equation

$$R' = 100 \left[1 - \frac{1}{a1} \int_{0}^{x} sf'(x)dx \right] \qquad (7),$$

is derived for the deposit of the removed material in relationship $< x_i$, where $f'(x)$ means the grain distribution curve achieved by differentiation of the crossing curve and where s is obtained by solution of equation (2) for the given values these days. The equation to be solved through calculations in stages gives the value of material which escaped from the cyclone

$$R'' = 100 \left[1 - \frac{1}{i(1-a)} \int_{0}^{x} (i-s)f'(x)dx \right] \qquad (8).$$

Fig. 10 shows the curves of the test material and of two dust removal materials for two separate fine dusts.

Fig. 10

Curve for dust with 20 and 45% deposit on sieve Nr. 70 and the corresponding deposited and escaped dust. D = 3 m; i = 0.5 m; v = 20 m/s; t = 20°; U = 1

Series and parallel cyclone circuits

These grain conglomeration relationships may be useful in solving a que-tion which often occurs and over which official opinion is divided. It consists of whether it is more profitable to link two cyclones in series or in parallel so as to improve the rate of dust removal. Calculations for brown coal dust of 27%/Nr. 70 show that by linking 2 identical cyclones, of 3 m in diam. and with a 0.5 m wide entrance cross section, in series 73% is deposited in the first and 8% in the second, or a total of 81% of material is deposited. By parallel linking of two cyclones with 25 cm wide entrance cross sections 79.8% total dust was deposited. Despite the fact that the rate of dust removal in a parallel circuit is slightly lower. The energy consumption is not as high as in series circuits, and installation capital and space are more limited, as one can use cyclones of smaller diameter (for example 1.5 insteam of 3 m). In fact the perfected total rate of deposit in a series circuit will be a little higher than calculated, for the first cyclone will not deposit quite as much as it is theoretically supposed to, leaving ~~more for the second. The calculated values clearly show that must carefully~~ decide whether the improved deposit justifies a rise in capital outlay, space and energy consumption.

Final considerations

These investigations show that unfortunately certain natural boundaries exist for simple mechanical dust removers. The most common being the cyclone. The construction and industrial directions should attempt to approximate the actual rates of dust deposit to those reached by calculations. While until

recently groping in the dark, we may now compare the real process to an ideal process, similar to that of thermodynamics, arrived at by careful calculation and graph methods, drawing the naturally set limits of the height of cyclone dust removal rate. By transposing the customs of thermodynamics, one may describe the relationship between the actual rate of dust removal and the ideal, as established by the procedure above, as the cyclone degree of quality. The question advanced by the lengthy investigations, which will be answered in another report, is how to draw full use from the cyclones' possibilities within the limits prescribed by nature.

As it has been possible to establish the natural limits of cyclone dust removal in this work, one should use necessary consideration in setting up requirements of rates of dust removal, and only require higher quality and more expensive dust removals when it is absolutely necessary.

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